High Magnetic Field Vortex Dynamics in $YBa_2Cu_3O_7$ from ^{17}O NMR

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We have used ^{17}O NMR spin-spin relaxation, along with spectrum measurements, to determine the *H-T* vortex phase diagram up to 24 T for aligned $YBa_2Cu_3O_7$ powder. There exists a pinning temperature $T_p(H)$, which is defined as the temperature above which all vortices are mobile. For $H \leq 10$ T, T_p is consistent[1] with the vortex melting temperature determined by resistivity[2] and torque measurements on high quality single crystals. Our new measurements show that from ~10 T to 24 T, T_p is field-independent, occurring at $T_p = 80$ K.

We measure T_p from spin-spin relaxation by the Hahn echo sequence, $\pi/2$–τ_e–π-acquire, where τ_e is varied. The $\pi/2$ pulse tips the nuclear spins to the XY plane; the π pulse refocuses the nuclear spins into a coherent "echo" at a time $2\tau_e$. Time fluctuating z-components of the magnetic field, such as can be produced by vortices, contribute to unrecoverable dephasing, attenuating the echo intensity. More specifically, spin echo decays result from two mechanisms: $^{63,65}Cu$ and ^{17}O spin fluctuations (resulting in Gaussian decay) and vortex motion (resulting in exponential decay). For temperatures above T_p, vortices move too fast to contribute to the decay, and the relaxation is accurately given by a Gaussian. Well below T_p, the $^{63,65}Cu/^{17}O$ fluctuations are negligible, and the decay is purely exponential, arising only from collective vortex motion. At intermediate temperatures the decay consists of *both* components,

$$M(t) = M(0)e^{-t/T_{2e}}e^{-(t/T_{2g})^2} \qquad (1)$$

where T_{2e} is the exponential relaxation time and T_{2g} the Gaussian relaxation time. We find that T_{2e} has an onset coincident with the pinning temperature determined by spectrum analysis (see Reference 1). In Figure 1 we plot the *H-T* phase diagram resulting from both the spectrum and relaxation experiments.

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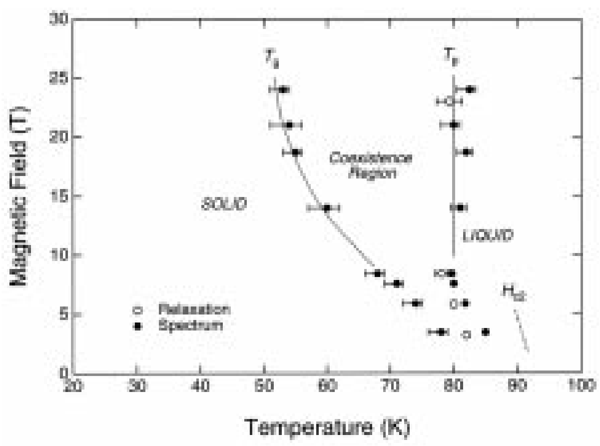

Figure 1. Phase diagram for vortex dynamics in $YBa_2Cu_3O_7$ aligned powders from ^{17}O NMR. Onset of vortex pinning is indicated as T_p, which at lower fields[1] was shown to be close to the melting transition, T_m, for clean, untwinned, single crystals. Filled circles are from spectral component analysis, after Reference 1. Open circles are from relaxation data, as described in text. Lines are guides to the eye.

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SUPERCONDUCTIVITY *Basic*

Specific Heat of Rare-Earth Borocarbides in High Magnetic Fields

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In the rare-earth borocarbides a competition exists between superconductivity and magnetism that results in a diversity of ground states. Depending on the rare-earth ion, some members of this series have either a magnetic or superconducting ground state, and in several systems, magnetism and superconductivity even coexistence at low temperature. Since the electron spin is involved in these interactions, studying the thermodynamic properties in the presence of an applied magnetic field that is large enough to influence the correlations in these systems is important.

A calorimeter, which was based on the thermal-relaxation technique, was constructed for the 18 T superconducting magnet at the NHMFL-LANL. This was used to measure the specific heat of single-crystalline $LuNi_2B_2C$ from 20 K to 1.6 K at different fields. With a zero applied field, $LuNi_2B_2C$ superconducts at 16 K, and a small residual linear contribution to the specific heat of ~0.9mJ/molK^2 was measured well below the phase transition, which is probably a consequence of a small amount of normal impurity phase. The upper critical field is anisotropic with a value of either ~12 T or ~9 T depending on whether the applied field is perpendicular or parallel to the c-axis of the tetragonal crystal structure, respectively. When the field is increased from zero, the linear contribution to the specific heat increases like $\sqrt{H}$ instead of H as in conventional superconductors where the normal component scales with the number of vortices. This could occur when the quasiparticles associated with the normal cores spread outside of the vortex cores because of the presence of nodal lines in the superconducting gap and are thereby limited by the distance between vortices.[1] These results are also consistent with recent measurements by M. Nohara *et al.*[2] on polycrystalline samples, implying the specific heat is isotropic.

We have also started investigating the field dependence of the low-temperature specific heat of $YbNi_2B_2C$. Unlike the other members of the series, this compound does not order, but instead has a heavy Fermi liquid ground state with a Kondo temperature of ~10 K. With these results, a comparison can then be made to the field-dependent transport properties using various theoretical models.

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Hole Doping Evolution of the Quasiparticle Band in Models of Strongly Correlated Electrons for the High-Tc Cuprates

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Quantum Monte Carlo (QMC) and Maximum Entropy (ME) techniques are used to study the spectral function of the one-band Hubbard model in strong coupling including a next-nearest-neighbor electronic hopping. These values of parameters are chosen to improve the comparison of the Hubbard model with angle-resolved photoemission (ARPES) data for undoped cuprates. A narrow quasiparticle (q.p.) band is observed in the QMC analysis at the temperature of the simulation T = t/3, both at and away from half-filling. Such narrow band produces a large accumulation of weight in the density of states at the top of the valence band. As the electronic density <n> decreases further away from half-filling, the chemical potential travels through this energy window with a large number of states, and by <n> = 0.70 it has crossed it entirely. The region near momentum X and Y in the spectral function is more sensitive to doping than momenta along the diagonal. The evolution with hole density of the quasiparticle dispersion contains some of the features observed in recent ARPES data in the underdoped regime. For sufficiently large hole densities the "flat" bands at X cross the Fermi energy, a prediction that could be tested with ARPES techniques applied to overdoped cuprates. The population of the q.p. band introduces a hidden density in the system which produces interesting consequences when the quasiparticles are assumed to interact through antiferromagnetic fluctuations and studied with the BCS gap equation formalism. In particular, a region of extended s-wave is found to compete with d-wave in the overdoped regime, i.e. when the chemical potential has almost entirely crossed the q.p. band as the density is reduced.[1]

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Indications of a Metallic Antiferromagnetic Phase in the Two Dimensional U-t-t' Model

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We present mean-field and quantum Monte Carlo results that suggest the existence of an itinerant antiferromagnetic ground state in the half-filled U-t-t' model in two dimensions. In particular, working at t'/t ≈ -0.2 we found that antiferromagnetic long range order develops at $U_{c\,1}/t \approx 2.5$ while a study of the density of states N(ω) and the response to an external magnetic field indicates that the system becomes insulating at a larger coupling 4, $U_{c\,2}/t$<6.

Specific Heat of the 2D Hubbard Model

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Quantum Monte Carlo results for the specific heat *c* of the 2D Hubbard model are presented. At half-filling, $c \approx T^2$ at low temperature and two distinct features are observed: a low temperature peak related to the spin degrees of freedom and a higher temperature feature related to the charge degrees of freedom. Away from half-filling the spin feature slowly disappears as a function of doping while the charge feature moves to lower temperature. Comparisons with experimental results for the high temperature cuprates are made.

Dirac Series: Low Temperature Transport Measurements of Superconductors and Semiconductors in Magnetic Fields to 800 T

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The Dirac Series is an initiative aimed at condensed matter physics and chemistry research utilizing implosively-generated magnetic fields up to 1000 T. One of the most ambitious goals of this program has been the attempt to achieve reliable electrical transport data on samples in this harsh electromagnetic environment. Trials in 1996 using 1-2 GHz signals, capacitively-coupled to semiconductor samples, demonstrated that by employing lithographically patterned transmission lines it was possible to keep Faraday pick-up voltages from the *B* field pulse within acceptable levels at the sample.[1] Subsequent developments in sample lithography have been incorporated to optimize signal-to-noise and to reduce eddy current heating in the sample region.[2] These improvements made possible significant low-temperature transport measurements on both high-T_c superconductor[3,4] and semiconductor samples[4] in the 1997 Series.

Epitaxially grown thin-films of the cuprate superconductor $YBa_2Cu_3O_7$ were measured with the magnetic field *B* directed parallel to the CuO planes ($J \parallel B \perp c$-axis) at an ambient temperature of 1.6 K and probe frequencies 0.9 to 1.7 GHz. We found an onset of dissipation at 150±10 T, the highest field yet reported. The measured critical field B_{c2}=(240±20) T is significantly above the paramagnetic limit for this material suggesting that a triplet state may exist at high *B* in YBCO, provided that $B \perp c$.

The 3D electron system confined in high-quality $Al_xGa_{1-x}As$/GaAs wide parabolic quantum well structures is a prime candidate for a predicted magnetic field-induced superconducting state.[5] We have determined the resistivity ρ_{zz} parallel to *B* in several steady and pulsed magnet configurations, giving a variety of field ranges to 800 T. Above 5 T, where magnetic depopulation forces all carriers into the lowest energy subband, ρ_{zz} shows a monotonic increase with *B* and additional structure in the field range 100 - 200 T. A possible decrease in ρ_{zz} above 200 T has been observed, however, further studies are required to confirm this.

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Magnetic Properties of Li-Doped La_2CuO_4

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La_2CuO_4, the prototypic single layer cuprate, can be hole-doped in two ways chemically: out-of-plane Sr-doping and in-plane Li-doping. In both cases, one hole is added to the CuO_2-planes per dopant atom. We have previously reported our work on the bulk properties of doped La_2CuO_4.[1] In the Li case, the doped material is insulating for all x. It is therefore remarkable that the Li-doping in other respects is identical to Sr-doping, which gives rise to metallic conductivity and superconductivity. The in-plane plaquette size, as determined by lattice constant measurements, depends only on the net hole concentration and not on the separate Li and Sr concentrations, the magnetism of La_2CuO_4 is suppressed at essentially the same rate for Sr or Li substitution, and even the rate of suppression of T_c in optimally-doped $La_{1.85}Sr_{0.15}CuO_4$ by added Li is relatively weak, being similar to that due to excess Sr doping and being several times smaller than that found for Zn substitutions. Here, we focus on new developments in our microscopic understanding of the magnetic properties of Li-doped La_2CuO_4. Our results on the optical properties of Li-doped La_2CuO_4 are reported elsewhere in this volume.

We have performed ^{139}La NQR measurements on $La_2Cu_{1-x}Li_xO_4$ for $x < 0.025$, i.e. in the range of Li concentration for which antiferromagnetic order persists.[2] Remarkably, the results are quantitatively identical to those previously reported for Sr-doped La_2CuO_4. In particular, a scaling behavior is observed in the dynamical susceptibility near the magnetic ordering temperature, consistent with finite-size scaling effects. At low temperatures ($T < 30$ K), the sublattice magnetization departs from its expected temperature dependence, and a recovery to nearly the undoped La_2CuO_4 value is observed. This is accompanied by a sharp peak in the relaxation rate. Similar phenomena have also been observed in muon spin resonance and elastic neutron scattering measurements and are consistent with the freezing out of a magnetic screening mechanism. The fact that all of these effects are nearly identical for Sr-doped La_2CuO_4 and Li-doped La_2CuO_4 calls into question the conventional interpretation of the Sr-doped data and may have implications for the eventual understanding of the observed high-temperature superconductivity.

Previously, we have reported the observation of a low-energy magnetic excitation in $La_2Cu_{0.5}Li_{0.5}O_4$ despite the fact that its ground state is that of a diamagnetic, atomically-ordered, insulating material.[3] This singlet-triplet excitation appears to be purely magnetic and is not accompanied by any structural distortions. Several theoretical studies have resulted from this work, and we are currently performing inelastic neutron scattering studies in collaboration with Gabriel Aeppli at the ISIS spallation neutron source in England to more completely elucidate the nature of this novel excitation.

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De Haas-van Alphen Effect in Conventional and Unconventional Superconductors in Magnetic Fields Well-Below Hc2

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De Haas-van Alphen (dHvA) in normal metals serves as a powerful tool for studying their electronic spectrum. At low temperatures with the magnetic field decrease, a superconducting state may set in, and the superconducting gap would finally smear away the dHvA oscillations in magnetization. Experimentally, however, dHvA oscillations have been observed in many type-II materials at magnetic fields, B, considerably smaller than the upper critical field, Hc2.[1]

Right below Hc2, in the mixed state, the superconducting order parameter is not homogenious leaving part of the normal density of states intact, and this results in a weakened, but yet measurable amplitude of the signal. With the further field decrease single vortices cease to overlap, and the main volume goes over into a "gaped" state, so that the dHvA oscillations are expected to drop down. Such a situation would take place if distances, d, between vortices remaining short compared with the penetration depth, begin to exceed the coherence length. In terms of the magnetic field values, this regime corresponds to the fields range Hc1 << B << Hc2.

The dHvA experiments in superconducting state attract much of attention because they make it possible to follow changes (if any) in the shape and sizes of the underlying normal phase Fermi surface at the superconducting transition. No changes are expected for the BCS-type superconductors. This is far from being obvious, however, in the case of such uncommon superconductors, as Ce- or U-based materials, or new high T_c oxides. For high T_c cuprates the critical field can also be so large that measurements of dHvA oscillations in a superconducting state may become the main tool to access electronic spectrum in the normal state. In addition, these materials are expected to possess a new type of the order parameter for which the energy spectrum may have along the Fermi surface symmetry points, or even whole lines with zeroes in the energy gap.

Consider a superconductor with such a line of zeroes at the Fermi surface. At a proper field direction the extremal electronic orbit would run along this line sensing no superconductivity gap. Therefore dHvA effect in the superconducting state could show a peculiar angle dependence with respect to the magnetic field direction, from which conclusions might be drawn regarding symmetry of the order parameter itself.

Another case is presented by superconductivity in layered oxides. A consensus is that superconductivity in cuprates is of the so-called "d-wave" type with zeroes at the four symmetry points of the (two-dimensional) Fermi surface. It is tempting to see if any peculiarities in the dHvA effect may provide an information on the gap symmetry.

To explore the problem, a general quasiclassical approach to studying properties of an anisotropic superconductor in presence of a magnetic field produced by the vortex lattice, has been developed[2-4] in frame works of the Gor'kov equations, that is, accurate enough to account for quantization of electronic levels in presence of a weakly non-homogenious magnetic field. Spectrum of excitations has been found in the main approximation, i.e., assuming a homogenious average field in the bulk.[2]

Quantum oscillations arise not only at crossing the chemical potential by an energy level, but also due to other singularities in the superconducting density of states, although the effect in the latter case is much weaker, if compared to the signal in the normal state.

dHvA for the three-dimensional Fermi surface for a superconducting gap with line of zeroes, would, indeed, show a pronounced dependence on the field direction. The effect is considerably reduced, however, by the scattering of electrons on periodic currents flowing in the vortex lattice. On the other hand, the dHvA signal remains small for a superconductor with a gap having only points of zeroes at the Fermi surface.[3,4]

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Doping in Cuprates as the First Order Metal-Insulator Transition

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This project is a continuation of our work together with P. Kumar.[1-3] Theoretically, the Mott insulator-to-metal transition is expected to be a first order transition provided when some variable (say, effective interactions) could be tuned thermodynamically. Doping, in addition to supplying carriers into the system, disturbs the network locally and randomly.

Although this is not a thermodynamic process, doping, nevertheless, forces a transition between insulating phase (at small dopant concentrations), and a metallic state (in overdopped samples). The metallic state is known to display the Fermi liquid features, and one might depart from that end, gradually decreasing number of carriers again. From this point of view, disorder, characteristic of alloying process, seems to be not of a crucial importance, especially if one recalls that a few stoichiometric materials, such as 123 or 124 compounds, also possess high enough temperature of the superconducting transition.

In References 1 through 3, it was shown (in terms of a realistic three-band model) that at low concentrations spectrum of carriers possesses narrow band features.[2] The spectrum is in agreement with the ARPES studies for insulators at reasonable choice of parameters.[3] Narrow bands, however, signal that when a hole is actually introduced into the band, formation of a polaron would be imminent. Polaronic cloud may be both of the lattice and of the magnetic origin.

A work is now in progress to study degradation of the metallic state with lowering of number of carriers. A better understanding can be achieved if doping due to "spill over" between bands (e.g., CuO_2-planes and CuO-chains in $YBa_2Cu_4O_8$) could be modeled. The main assumption of the model is that formation of localized spins on the Cu-sites takes place not due to Hubbard-like strong local interactions, but, rather due to formation of lattice distortions around Cu-sites. Such a model leads to some phase separation effects, as it was first shown in Reference 4. Recent experiment in stoichiometric $ErBa_2Cu_4O_8$, indeed, display an inherent inhomogeneity.

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Magnetization Measurements on $Ba_{0.6}K_{0.4}BiO_4$ (BKBO)

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As a follow-up to our previously reported dHvA measurements on BKBO we undertook a more complete measurement of the magnetic phase diagram of this material than had been previously published. The conclusions of this work are: The normal state susceptibility between 35 and 300 K shows that, while there are about 0.1% magnetic impurities in the samples, they all show a Pauli paramagnetism, after subtracting the diamagnetic core contributions, consistent with the number of carriers predicted by band theory. Next, the measured values of Hc_2 and the reversibility field, H_R, measured between T = 1.8 K and 32 K in fields from 0.001 T to 27 T, deviate significantly from standard theory. Our results are in general agreement with previous lower field measurements, but show a marked enhancement of Hc_2 and H_R, almost appearing to increase without limit as T = 0 is approached as shown in Figure 1.

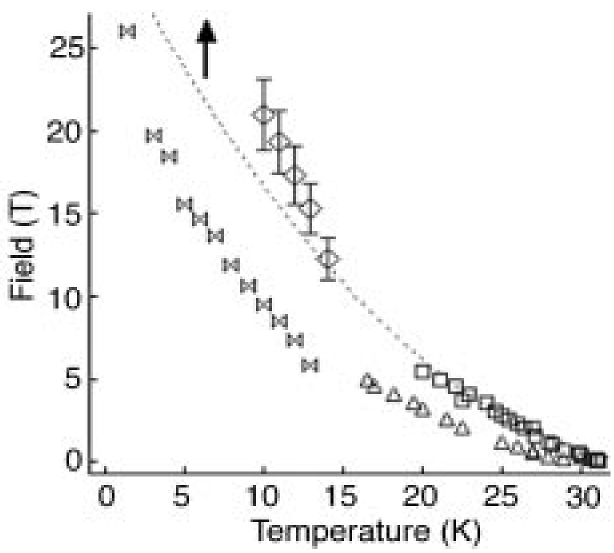

Figure 1. The critical fields, Hc_2 - ◇ and □, and the reversibility fields, ⋈ and △, as a function of temperature for $Ba_{0.6}K_{0.4}BiO_4$.

In this figure the dotted curve is a fit to earlier data. This marked increase of Hc_2 as zero temperature is approached suggests that BKBO might be a candidate material for experiments designed to observe re-entrant superconductivity. Finally, we note that BKBO may exhibit a phase transition from the normal to the superconducting state of thermodynamic order higher than two. This conclusion is based on the fact that neither the specific heat nor the magnetic susceptibility show discontinuities as the transition from the superconducting to the normal state is crossed. A paper reporting these results now has been submitted, and this work has formed part of the basis of the Ph.D. thesis of Mr. Donavan Hall, who will receive his Ph.D. in December 1997, and is now employed by the NHMFL.

High Magnetic Field Studies of the Spin Gap in Optimally and Underdoped $YBa_2Cu_3O_y$

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One of the most actively researched questions in understanding the cuprates concerns the origin of a strong suppression of the spin susceptibility with decreasing temperature first observed in NMR Knight shift measurements in underdoped $YBa_2Cu_3O_{6.63}$.[1] This suppression has come to be known as the spin gap. Recently it has become clear that the spin gap can be observed in optimally doped $YBa_2Cu_3O_{6.96}$ as well.[2] We are studying the response of the spin gap in $YBa_2Cu_3O_{6.96}$ to applied magnetic fields to better understand its nature and origin.

We have made extensive and precise measurements of the field dependence of the normal state spin susceptibility of $YBa_2Cu_3O_y$ for y = 6.96 and 6.63. These measurements have been obtained by means ^{17}O Knight shift measurements made in the resistive 24 T magnet at fields of 24 T and 16 T along with a 9 T superconducting solenoid at Ohio State University. We have performed these experiments on aligned powders, which enable us to make measurements with the field applied both parallel and perpendicular to the crystalline c-axis (perpendicular to the CuO_2 planes). ^{133}Cs NMR has been used to allow precise determination of the applied field in which the measurements were made. In order to obtain the highest accuracy, these measurements have been corrected to provide agreement with results obtained on the same sample in a high homogeneity 8.8 T superconducting magnet.

Unexpectedly, we find that the spin susceptibility exhibits significant field dependence in the normal state of $YBa_2Cu_3O_y$, even above the *zero-field* T_c. The field dependence is manifested as a downward shift in temperature of the onset of the spin gap. When the magnetic field is applied perpendicular to the CuO_2 planes is the rate of suppression of the spin gap is approximately given by $\Delta T/\Delta H \approx$ 0.5 K/T.

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Quasiparticles in d-Wave Superconductors

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Quasiparticle Contribution to Thermodynamics and Transport in Vortex State. A theory of the vortex state in clean and disordered d-wave superconductors was constructed with an eye towards understanding recent experiments on cuprate and heavy fermion superconductors. The simple underlying picture is that, in contrast to classic s-wave systems, the few bound states in vortex cores are irrelevant, and the principal contribution arises from the extended states located in momentum space near the d-wave nodes. In such a case, there is a range of fields and temperatures, which we argue to be surprisingly large in the cuprates, where the principal contribution to the magnetic field dependence of both thermal and transport properties arises from the changes in quasiparticle occupation number due to the Doppler shift of the quasiparticle energy in the vortex superflow field. Calculations of the density of states and specific heat in a semiclassical approximation including the effects of impurity scattering suggest that recent specific heat experiments on YBCO in a magnetic field exhibiting varying dependences on magnetic field at low temperatures may be understood in terms of sample variability. Recent predictions of scaling of thermodynamic properties in the variable $T/H^{1/2}$ were shown to break down when the impurity bandwidth exceeds either the temperature or the average Doppler shift.

Transport properties were also considered in this formalism. Quasiparticles are considered to be scattered only by those processes that are present in the zero-field state, and the field dependence is therefore directly related to the temperature dependence in zero field. In the case of strong impurity scattering, scaling is only approximately obeyed even in the clean limit. Results for electronic thermal conductivity are in good agreement with recent experiments on YBCO and UPt_3. New behavior is predicted at higher energy scales, necessitating new measurements at fields of order 30 T.

Residual Density of States in 2D Disordered d-Wave Superconductor. (With K. Ziegler, MPI-Stuttgart). Exact lower bounds for the residual density of states in a strictly 2D d-wave superconductor were obtained in a model with off-diagonal d-wave order and site disorder for a large class of disorder distributions, including Gaussian and Lorentzian. This is important in the context of recent assertions that the standard t-matrix approximation for dilute impurity scattering breaks down in 2D, leading to a critical density of states with N(0) = 0. Similar bounds were obtained for models of 2D Dirac fermions.

Off-Diagonal Scattering from Order Parameter "Holes" in d-Wave Superconductors. Conventional models of impurity scattering assume a constant order parameter, whereas it is well known that the order parameter in a d-wave system is suppressed around a strong local potential over a length scale of order the coherence length. If this length is sufficiently short, as in the cuprates, one can model the suppression as an off-diagonal delta-function perturbation with weight determined self-consistently, and perform the disorder average using standard methods. This leads to a new resonance in the impurity self-energy and has an important influence on the low-energy quasiparticle scattering rate. The temperature dependence of the microwave conductivity in YBCO is quasilinear, in contrast to the quadratic dependence predicted by standard "dirty d-wave" theory; the new resonance may account for this discrepancy.

Far-Infrared Properties of Superconducting $YBa_2Cu_3O_{7-\delta}$ Films in High Magnetic Fields

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The reflectance ($\mathfrak{R}$) and transmittance ($\mathfrak{I}$) of ab-plane-oriented $YBa_2Cu_3O_{7-\delta}$ films have been measured over the frequency range from 35 to 600 cm^{-1} at temperatures between 4.2 K and 300 K and in magnetic fields up to 27 T. The frequency-dependent optical conductivity is determined directly from the $\mathfrak{R}$ and $\mathfrak{I}$ spectra. The temperature dependence of zero-field data are consistent with a two-component dielectric response, with the free carriers component condensing to form the superfluid below T_c. However, when applying strong magnetic fields (with H perpendicular to the ab plane and with unpolarized light) at low temperatures (4.2 K to 50 K) the conductivity spectrum shows no discernible field dependence. This observation differs from other previous measurements in this temperature range. Only at fields and temperature where the DC resistance is not zero (e.g., above ~60 K at 27 T) is there a field-induced effect in far-infrared response. This effect is attributed to flux motion in the "flux liquid" regime of the T-H phase diagram.

Vortex Structure and Vortex Correlations in the Presence of High Magnetic Fields and Point Disorder in Clean and Irradiated $YBa_2Cu_3O_7$

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Since the discovery of the high temperature superconductors in 1988, the complexity of its magnetic phase diagram has been evident. A rich new vortex liquid phase has emerged, separated from the solid phase by a clear first order vortex lattice melting transition in clean crystals. In transport measurements this melting transition is detected as an abrupt, practically discontinuous, drop of the electrical resistance.[1] At high magnetic fields, features of this sharp first-order phase transition broaden and eventually terminate altogether,[2] suggesting the existence of a critical point (CP). Little is yet established about the nature of the CP (i.e., whether it is an end point or a multicritical point) since little is known about the vortex solidification process above it. In particular, the state of the vortex matter at high fields, where its static and dynamic properties are ruled by point-like disorder, is still obscure and has been a subject of several recent theoretical proposals.[3]

We have performed transport measurements using the flux transformer geometry in the mixed state of the high temperature superconductor

$YBa_2Cu_3O_7$ (YBCO). We have studied the vortex dynamics and vortex correlations in the solid phase of clean (untwinned) crystals in the presence of uniform and non-uniform current distributions. In the sample studied, the first order melting transition is seen to persist up to a CP of 12 T. At this field a clear change of slope is seen in the line marking the vanishing of the electrical resistance (see Figure 1). At higher fields the resistance goes continuously to zero.

In the vortex-solid phase the in-plane critical current shows a maximum as a function of field ("peak effect") (see inset in figure) at a well defined line in the H-T phase diagram. This line is located well below the CP, is independent of temperature at low temperatures, decreases with temperature close to the melting line, and intersects it at a finite field (see figure). It is possible that this line separates at the low fields ordered vortex lattice (that melts via a first order melting transition) from a high-fields vortex-glassy state (that undergoes a continuous transition).

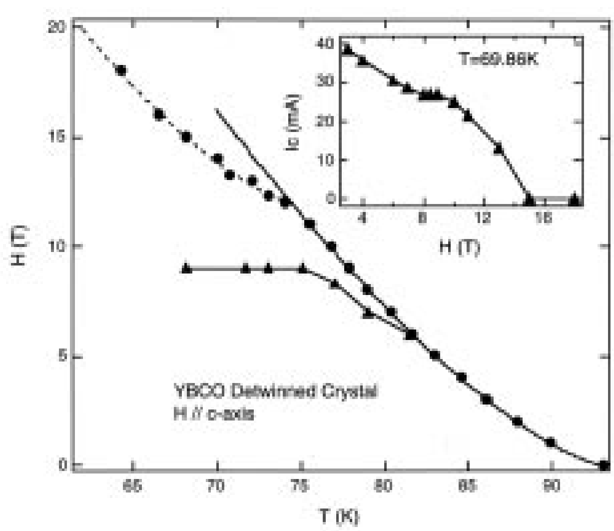

Figure 1. Composite H-T phase diagram of a clean YBCO crystal. This crystal exhibited a critical point (CP) at about 12 T. Full circles denote the point where the resistance is seen to vanish, discontinuously below CP and continuously above CP. The full triangles denote the point where the critical current shows a peak. Inset: Field dependence of the critical current of the same YBCO crystal, showing a broad peak at H = 9 T.

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Diagonalization in Reduced Hilbert Spaces Using a Systematically Improved Basis

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We proposed a method to improve the accuracy of approximate techniques for correlated electrons that use reduced Hilbert spaces. As a first step, the method involves a change of basis that incorporates exactly part of the short distance interactions. Then a Hilbert space truncation[1] is performed in the new variables. The method was successfully tested using the Heisenberg and t - J models on 2-leg ladders and chains, including estimations for ground state energies, spectra of excited states, and the dynamical spin structure factor.[2]

Right now we are using the method described above to study the quasiparticle dispersion and spectral function A(p,w) of the t - J model near half-filling on 2-leg and 4-leg ladders. The new technique allow us to reach cluster sizes and densities that cannot be studied with exact diagonalization methods. The results show how the dispersion of a hole in an antiferromagnet at half-filling evolves continuously into a quasi-free dispersion at intermediate hole densities.

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Insulator-Metal Transition in One Dimension Induced by Long-Range Electronic Interactions

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The effects of a long range electronic potential on a one dimensional commensurate Charge Density Wave (CDW) state are investigated. Using numerical techniques it is shown that a transition to a metallic ground state is reached as the range of the electron-electron repulsion increases. In this metallic state, the optical conductivity exhibits a large Drude weight. Possible interpretations of our results are discussed.[1]

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Spectral Functions of Lightly Doped Antiferromagnets Using Dressed Hole Operators

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Literature addressing the existence of hole pockets in experiments for the high-T_c cuprates and in theoretical analysis of electronic models of correlated electrons is reviewed. It is argued that the issue is not conclusively resolved, both in theory and experiments. The apparently large Fermi surface observed in numerical studies of the doped Hubbard and t-J models suggests the presence of (1-x) carriers (with (x) the concentration of holes). This is in contradiction, however, with results obtained in similar calculations for the Drude weight. To address such paradox, dressed operators are here used. Their spectral decomposition is analyzed specially using the t-J model on ladders, but considering also chains and two dimensional (2D) clusters. The results are contrasted against those obtained with the standard bare operators. It is concluded that substantial changes in the spectral weight can occur by replacing the bare hole creation operator by its dressed version. Large Fermi surfaces in angle-resolved photoemission (ARPES), obtained by the sudden removal of an electron, may not be in contradiction with a visualization of the normal state of lightly doped antiferromagnets as composed of a gas of spin polarons with energies approximately obtained from the rigid band doping of the half-filled dispersion. The ideas discussed here are very general and they can be applied to a variety of problems where quasiparticles are strongly dressed by low energy excitations of the medium in which they are immersed.[1]

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High-Field c-Axis Negative Magnetoresistance and Upper Critical Field in $Bi_2Sr_2CaCu_2O_{8-\delta}$

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The upper critical field line of the high temperature superconductors has remained as one of the less explored properties of these materials. In part, this is due to the exacerbated role of thermal fluctuations that make the transition from the superconducting to normal states smooth and without any particular features. Secondly, the high

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fields involved have restricted measurements to either high temperatures or low-Tc members of the cuprate family. In particular, these later studies found a positive curvature instead of the conventional negative curvature expected from the classical WHH (Werthamer-Helfand-Hohenberg) theory.

We have performed high magnetic fields c-axis magnetoresistance measurements on the superconducting and normal state of the high temperature superconductor $Bi_2Sr_2CaCu_2O_{8-\delta}$, with T_c = 94 K. Our work was carried out at the facilities of the NHMFL-LANL, using pulsed (up to 60 T) and DC (up to 18 T) magnetic fields. In the temperature range below T_c we find that at low fields, in the regime dominated by superconducting fluctuations, the magnetoresistance is positive. At the same temperatures, however, we reach a high field regime characterized by negative magnetoresistance (see inset in Figure 1). This crossover was also observed before by Ando *et al.* in a low-T_c, single-layer cuprate. In our crystals, the negative magnetoresistance is also observed at temperatures twice T_c, well into the normal state. Thus, by studying the crossover between positive and negative magnetoresistance we can estimate the upper critical field H_{c2} of this compound. We obtain an H_{c2} practically linear, with a very slight upward curvature, from Tc down to T = 25 K (see figure). At temperatures below 25 K the negative magnetoresistance regime is not reached with our 60 T pulse, thus preventing us from measuring the low temperature portion of the H_{c2} line.

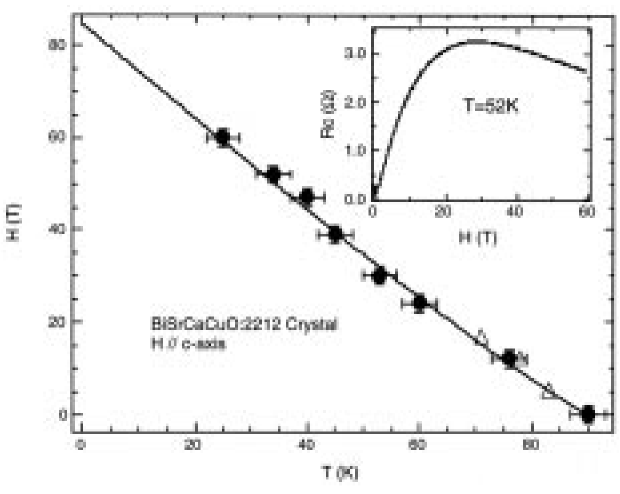

Figure 1. Shown is the temperature dependence of the upper critical field. Full circles are data points obtained in pulsed field experiments. Open triangla are data obtained in DC field experiments. The solid line is a guide to the eye. Inset: c-axis magnetoresistance in a pulsed field experiment at T = 52 K.

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Magnetoresistance in Granular Electron-Doped Superconductors

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Superconducting granular systems display a wealth of physical behaviors manifested in the electrical transport properties across the superconducting-insulator (SI) transition, such as insulator, local superconductivity, metallic behavior, and global superconductivity. In these systems the superconducting critical temperature T_{ci} is not affected by the SI transition suggesting that superconductivity is suppressed when the long range order in the phase coherence of the order parameter is lost.

One of the most interesting features of granular systems is observed in samples belonging to the so-called dielectric side of the SI transition.[1-3] In this regime, a drastic increase of the resistance, R(T), due to development of superconductivity is frequently observed below T_{ci}. This increase in R(T) can be explained by the semi-phenomenological two-fluid theory of superconductivity, as suggested elsewhere.[1,4] According to this theory, the portion of charge

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carriers which remains in the normal fluid below the transition temperature T_{ci} varies as $(T/T_{ci})^4$ resulting in a gradual increase in R(T) by a factor of $(T/T_{ci})^{-4}$.

At the NHMFL-LANL we focus on the effect of superconductivity on the macroscopic conduction behavior of polycrystalline samples of the electron-doped superconductor $Ln_{2-x}Ce_xCu_{4-y}$; Ln = Sm, Eu.[5] In general, these materials are best described by being comprised of small superconducting islands embedded in an insulating matrix[6,7]—a structure similar to a granular superconductor. In a recent work,[8] we have performed electrical resistance, magnetoresistance, and magnetization measurements in polycrystalline samples of $Sm_{1.83}Ce_{0.17}CuO_{4-y}$. From these measurements we have found that: (1) appreciable diamagnetism develops below T_{ci} = 17.5 K; (2) the latter is accompanied by a fractional drop in the magnitude of R(T) at T_{ci}; (3) an abrupt increase in the magnitude of R(T) below the mean-field superconducting transition T_{ci}. Such an increase in the magnitude of R(T) was found to be rapidly suppressed by the application of magnetic fields of 8.8 T.

By considering the excess of resistance $\Delta R(T, H)$, i.e., the computed resistance exceeding the normal state resistance value expected from a simple polynomial extrapolation of R(T, H=0) down to lower temperatures, we have found that, for $0.6 < (T/T_{ci}) < 1$, $\Delta R(T, H)$ is proportional to $(T/T_{ci})^{-4}$. For lower temperatures, $(T/T_{ci}) < 0.6$, $\Delta R(T, H) = \Delta R_0(H)(T/T_{ci})^{-1/4}$.

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Upper Critical Magnetic Field of $LuNi_2B_2C$

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$LuNi_2B_2C$ is a non-magnetic member of the nickel borocarbide superconducting family that exhibits a high T_c of about 16 K. Although magnetoresistance measurements are consistent with an isotropic normal state,[1] the upper critical field exhibits an anisotropy of about 30% for fields parallel or perpendicular to the c-axis.[2] The presence of anisotropy suggests a reduced dimensionality for the superconducting state which could, in turn, result in positive curvature in H_{c2} (T) at low temperatures.[3]

We used a standard four terminal resistance technique and measured $H_{c2}(T)$ (defined as the midpoint of either an isothermal or iso-field resistance transition) of a polycrystal sample of $LuNi_2B_2C$ from about 20 mK to 1 K. We fit the data below 200 mK to a straight line and find a slope of -0.2 ± 0.01 T/K and $H_{c2}(0) = 9.35 \pm .002$ T.

Though we do not observe positive curvature, the absence of saturation to temperatures as low as 20 mK ($T/T_c = 0.0012$) is surprising. Subsequent work will focus on single crystal samples of this material.

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Momentum, Temperature, and Doping Dependence of Photoemission Lineshape in High T_c Materials

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The anomalous momentum and temperature dependence of the spectral lineshape in data from underdoped $Bi_2Sr_2CaCu_zO_{8+\delta}$ indicates that quasi particles are strongly coupled to collective excitations centered near Q=(π,π). We find in underdoped material that the quasiparticle peak in the spectrum that occurs for momentum at α the Fermi surface along the (π,π) direction, is replaced by a broad hump centered at energy of order 150 mev for momenta on the Fermi surface β near (π, o). This result is interpreted as the inelastic shake off cloud of collective modes when a bare photo hole is created at β. That this effect is observed at β and not at α is consistent with the antiferromagnetic spin model since the spin susceptibility is peaked at Q=(π,π), thereby strongly coupling states, which are nearly degenerate at the corresponding β points near (o,± π). This effect does not occur at α since the states mixed by momentum Q are of high energy and the shake off effects are weak. These results give support for the spin fluctuation approach to high T_c superconductivity since the collective modes effects are consistent with a strong pairing interaction of the excitations near β where the observed flat bands make a large contribution to the density of states.

Numerical Study of Spin-Charge Separation in One Dimension

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The problem of spin-charge separation in one dimension is studied in the one band Hubbard model for the behavior of the single particle Green's function and the spin and charge susceptibilities. Using the quantum Monte-Carlo approach, the numerical results were continued to the real axis using the maximum entropy method. While the results showed two peaks for momentum away from the Fermi surface, we found that improved results could be obtained by fitting the imaginary time Green's function to results from the Luttinger model solution with two velocities as fitting parameters. The regions of momenta where spin-charge separation is seen is well beyond the region of linear dispersion of the excitation spectrum.

Quasi Particle Induced Gap Relaxation and the Interaction Between Quasi Particles

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In contrast to low T_c superconductors, when a quasi particle is created in a high T_c material, the energy gap is locally reduced in its vicinity. We have studied how this reduction influences the interaction between quasi particles. For s-wave paring we find that the quasi particles tend to form topological textures where the quasi particles segregate into antiphase domain walls between superconducting regions where the order parameter phase differs by π. The Bogoliubov-de Gennes equations were solved self consistently using a 30 x 30 2d square lattice and a closed ring of quasi particles was obtained with the phase of the gap inside and outside the ring differing by π.

Spectral Properties of Quasi Particle Excitations Induced by Magnetic Moments in Superconductors

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The consequences of localized classical magnetic moments in superconductors were explored and their effect on the spectral properties of the intra gap bound states were studied. We find that above a critical moment, a localized quasi particle excitation in an s-wave superconductor is spontaneously created near a magnetic impurity, inducing a zero temperature quantum transition. In contrast, the spin unpolarized ground state of a d-wave superconductor is found to be stable for any value of the magnetic moment. The depression of the order parameter Δ is studied, showing that Δ is strongly reduced in the vicinity of the impurity. The results of the T-matrix approximation, with $\Delta = \Delta_o$ in the absence of the impurity, are compared with the results of the self consistent Bogoliubov-de Gennes equations. Qualitative agreement between these two schemes for the spectral function is found in the regime where the coherence length is larger than the Fermi wave length of the paired particles.

Transverse and Longitudinal Critical Fields in $Tl_2Mo_6Se_6$

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Rasolt and Tesanovic[1,2] predicted that under certain circumstances high external magnetic fields, $H>H_{c2}$, could induce superconductivity in some type II superconductors. They proposed that when the Landau levels are included and the BCS theory solved rigorously, both the diamagnetic pair breaking and the Pauli pair breaking can be circumvented in the high magnetic field limit. This effect is particularly enhanced when the material is near the quantum limit ($H>H_{ql}$) where all the electrons fall below the lowest Landau level. Accordingly, magnetic fields beyond H_{c2} can increase T_c by enhancing the density of states at the Fermi level. The materials of choice for the experimental search for the phenomena are low-carrier-density semiconductors and semimetals, in which the quantum limit can be reached with available laboratory fields many of which are superconductors in zero fields. Materials with low effective g value ($g^*<2$) would be preferable to insure a large range of H field over which both spin states are populated. The combination of low electron-density-of-states, low-energy phonon mode, unusual bulk superconducting ground state[3] and uncomplicated structural properties make $Tl_2Mo_6Se_6$ a suitable material for the search of this effect. It also has been shown that the carrier density and the superconducting properties of this compound can be tuned using uniaxial stress.[4] The objective of this research is to test the above mentioned prediction in this compound using uniaxial stress to tune the Fermi surface and high magnetic fields.

We conducted a series of high field, DC (20 T) and pulsed (60 T) experiments between 350 mK and 7 K to characterize the temperature dependence of H_{c2} both in the transverse and longitudinal direction. The longitudinal studies will be free of the Lorentz force (flux flow and orbital effects) and therefore should be more promising. Our results show that H_{c2} transverse behave in a non conventional manner as reported earlier,[3] the longitudinal H_{c2}, behaves in a conventional way $H_{c2}(T) = H_c(0)[1-(T/Tc)^2]$, with $H_c(0) = 25$ T.

In the case of the longitudinal field, beyond 25 T, the pulsed experiments reveal a strong and nearly linear magnetoresistance with a negative dR/dH up to 50

T. The magnitude dR/dH decreases with increasing current. dR/dH in this direction is at least an order of magnitude higher than the very weak negative dR/dH below 30 T previously reported in the transverse magnetoresistance.

Work is in progress to study the effect under uniaxial stress and lower temperatures. Parallel effort is being pursued to improve the quality of the crystals so as to be able to observe the Landau oscillations.

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